Hydrogen Explosion Hazards

Unv. of Houston Hydrogen Symposium

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OUTLINE

- Purpose
- Background
- Accidental Unconfined H_2 Vapor Cloud Explosion (VCE)
- H_2 VCE Tests
  - Unconfined
  - Jet Release
  - Vented
- H_2 VCE Blast Load Prediction Overview
- Conclusions

Purpose

- Provide broad overview of explosion hazards associated with a release of hydrogen in an industrial setting:
  - Unconfined vapor cloud explosion (VCE)
    - Establish that an unconfined hydrogen VCE is credible
  - Vented explosion (i.e., within an enclosure)
  - Blast load prediction approaches

Background (1 of 2)

- Hydrogen poses a fire and explosion hazard
- Not unique, and other commonly encountered fuel sources also pose fire and explosion hazards
  - Natural gas & propane (home, BBQ grills, LNG, etc.)
  - Gasoline
- Important to recognize the hazard and properly manage the risk
  - This presentation limited to hydrogen explosion hazard
- Guidance is available:
  - NFPA codes & standards (NFPA 2, NFPA 69, etc.)
  - Hydrogen Safety Panel

Background (2 of 2)

- Papers and conference presentations upon which this presentation is primarily based:

1) Malik, D.R., W.B. Lowry, E. Vivanco and J.K. Thomas (2023) "Very-Lean Hydrogen Vapor Cloud Explosion Testing," Process Safety Progress (AIChE GCPS, Houston, TX, March 12-16, 2023).
2) Jallais, S., E. Vyazmina, D. Miller and J.K. Thomas (2018) "Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment," Process Safety Progress, 37(3): 397-410.
3) Thomas, J.K., J. Geng, O.A. Rodriquez, et al. (2018) "Potential for Hydrogen DDT with Ambient Vaporizers," Mary Kay O'Connor Process Safety International Symposium, College Station, TX, October 2018.
4) Horn, B.J., O.A. Rodriquez, D.R. Malik and J.K. Thomas (2018) "Deflagration-to-Detonation Transition (DDT) in a Vented Hydrogen Explosion," AIChE GCPS, Orlando, FL, April 22-25, 2018.
5) Thomas, J.K. and D.R. Malik (2017) "Ammonia and Hydrogen Vapor Cloud Explosion Testing (A Tale of Two Gases)," 62nd Annual Safety in Ammonia Plants and Related Facilities Symposium, New York, September 10-14, 2017.
6) Thomas, J.K., C.D. Eastwood and M.L. Goodrich (2015) "Are Unconfined Hydrogen Vapor Cloud Explosions Credible?" Process Safety Progress, 34(1): 36-43.
7) Miller, D., C.D. Eastwood and J.K. Thomas (2015) "Hydrogen Jet Vapor Cloud Explosion: Test Data and Comparison with Predictions," AIChE GCPS, Austin, TX, April 26-30, 2015
8) Thomas, J.K., M.L. Goodrich and R.J. Duran (2013) "Propagation of a Vapor Cloud Detonation from a Congested Area into an Uncongested Area: Demonstration Test and Impact on Blast Load Prediction," Process Safety Progress, 32(2): 199-206.
9) Thomas, J.K., R.J. Duran and M.L. Goodrich (2010) "Deflagration to Detonation Transition in a Lean Hydrogen-Air Unconfined Vapor Cloud Explosion," Mary Kay O'Connor Process Safety International Symposium," College Station, TX, October 27, 2010,

- Accidental Unconfined H_2 VCEs

Accidental H_2 VCEs (1 of 8)

- Focus on accidental H_2 VCE history is on unconfined H_2 VCEs:
  - Doubts expressed as to whether unconfined H_2 VCEs are credible
    - Hydrogen is light (buoyant) – "so doesn't it just float away?"
    - High has a high likelihood of immediate ignition – "so doesn't it just form a jet fire?"
- Many H_2 VCEs not reported (as with all explosions)
- Listing in 2015 paper remains a good summary, but incidents have continued to occur
  - Thomas, J.K., C.D. Eastwood and M.L. Goodrich (2015) "Are Unconfined Hydrogen Vapor Cloud Explosions Credible?" Process Safety Progress, 34(1): 36-43

Accidental H_2 VCEs (2 of 8)

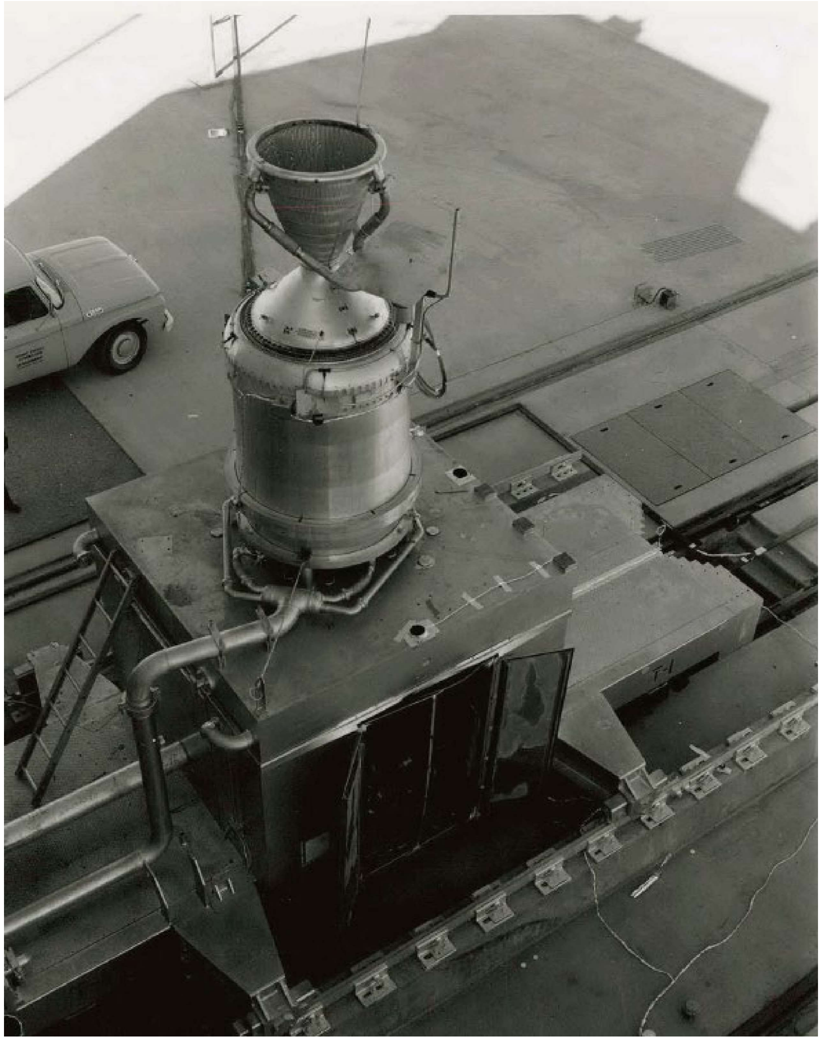
- Ordin (1974):
  - Reviewed incidents from NASA operations
  - 62% of releases to environment ignited (i.e., 38% did not)
  - At least 9 unconfined H_2 VCEs due to releases through vent stacks & failed components
  - Some reported to be detonations, up to 20 lb_m (9.1 kg) of TNT-equivalent
- Zalosh and Short (1978):
  - Reviewed > 400 H_2 accidents (1965 – 1977)
  - Slightly > ½ of incidents were explosions
  - 3/4 of incidents involved H_2 gas

Accidental H_2 VCEs (3 of 8)

- Other reviews & data collections:
  - H_2 Safety Panel “H_2 Incident Examples” report (2020, 67 incidents)
  - H_2 Incidents database (2014 paper data review)
    - 7 events clearly unconfined H_2 VCEs
    - Sarnia and another similar incident
    - Several similar to Muskingum River Plant incident
- Selected reported unconfined H_2 VCEs:
  - Jackass Flats, NV, 1964
  - Polysar, Sarnia, Ontario, 1984
  - Muskingum River Plant, Beverly, OH, 2007
  - Air Products, Santa Clara, CA, 2019

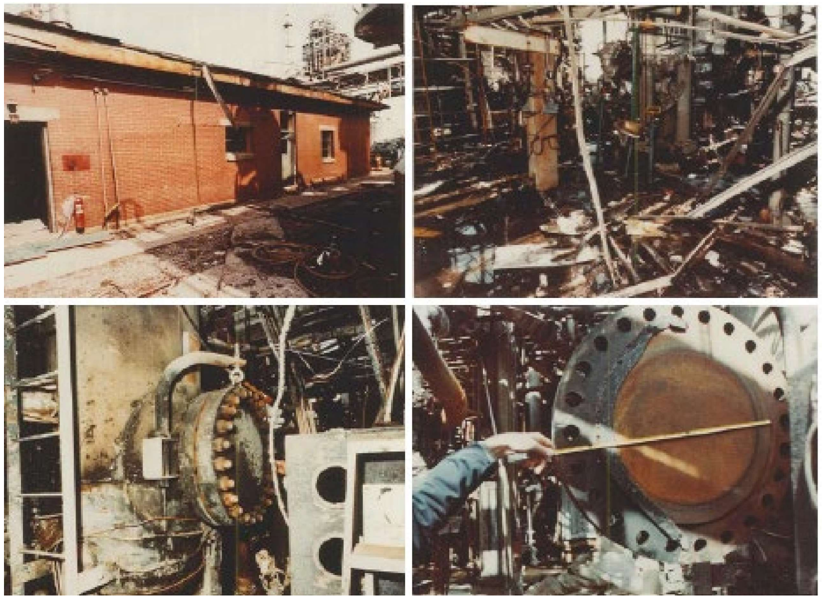
Accidental H_2 VCEs (4 of 8)

- Jackass Flats (Jackass Flats, NV, 1964):
  - Reider, Otway & Knight, 1965
  - Rocket motor test program
  - H_2 test run without ignition (by design)
  - Release from 3,400 psi (23.6 MPa) upward through convergent-divergent nozzle
- Flowed 13 sec. before unintentional ignition
- Estimated 200 lb_m (90 kg) of H_2 (10% of that released) involved in VCE
- VCE determined to be deflagration
  - Flame acceleration due to jet turbulence



Accidental H_2 VCEs (5 of 8)

- Polysar petrochemical complex (Sarnia, Canada, 1984):
  - MacDiarmid & North, 1989
  - Release of H_2 from partially failed gasket on compressor in open-sided shed (i.e., not completely unconfined)
  - 700 psi (48 bar), 10 to 15 sec before ignition, released 30 kg of H_2
  - Building damage at 500 ft (150 m) consistent with 1.1 psi (0.076 bar) overpressure
  - Consistent with detonation of 26 kg of H_2 (BST); high fraction of estimated release



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Accidental H_2 VCEs (6 of 8)

- Muskingum River Plant (Beverly, Ohio, 2007):
  - Rupture disc failure on outdoor hydrogen storage tank vent line during tank filling operations
  - Tank pressure at roughly 2000 psi
  - Release continued for roughly 10 sec. before ignition
  - WHA estimated 18 kg H_2 released
  - Killed driver, heavily damaged adjacent buildings

Accidental H_2 VCEs (7 of 8)

- Air Products (Santa Clara, CA, 2019):
  - H2 Safety Panel Report (June 2021)
  - Filling H2 trailer (gaseous), gas cylinders loaded to 7,200 psi
    - Did not involve liquid H_2
  - Attempt to repair leaking valve results in release from open pipe
  - Explosion within seconds, followed by jet fire; other cylinders to release through PRDs and contribute to fire
  - Window failure at 125 feet

Accidental H_2 VCEs (8 of 8)

- Based on review of accidental unconfined H_2 VCE information:
  - They have happened regularly in the past,
  - They have happened recently, and
  - It is therefore reasonable to expect will happen in the future.

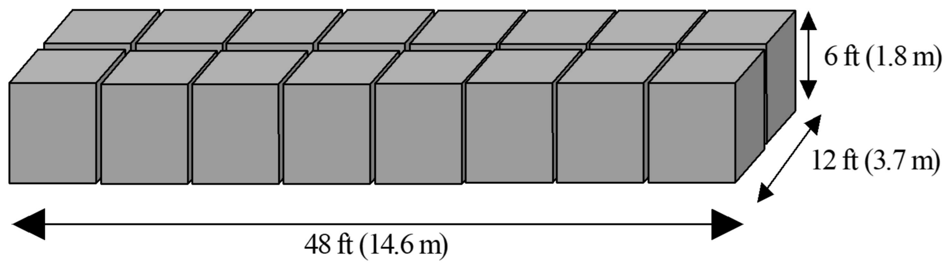
• Unconfined H_2 VCE Tests

Unconfined H_2 VCE Tests

- Numerous unconfined H_2 VCE tests by multiple organizations have been performed
- Unconfined H_2 VCE testing has shown the potential consequences of H_2 release into unconfined area with delayed ignition:
  - Can produce significant blast loads from unconfined H_2 VCE,
  - Can achieve deflagration-to-detonation transition (DDT) at moderate congestion levels
- Selected BakerRisk test programs illustrated on following slides

Unconfined Lean H_2 VCE Testing

- Congested volume consisted of a regular array of vertical circular tubes:
  - 2.375-in (60 mm) tube dia.
  - 45 per 6-foot cube (+ corner supports)
  - "Medium" congestion level
- Center ignition (near grade)



Schematic of VCE Test Rig

Photograph of VCE Test Rig

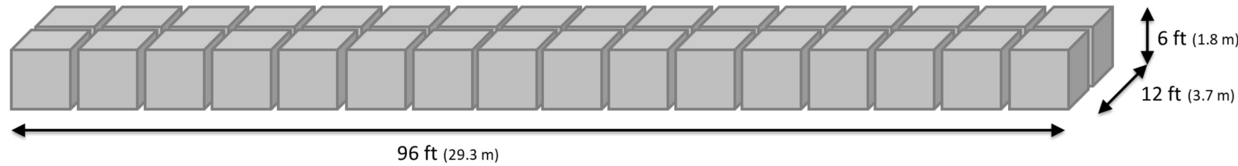
18% Hydrogen (ER = 0.52)

20% Hydrogen (ER = 0.60)

22% Hydrogen (ER = 0.67)

Unconfined Very Lean H_2 VCE Testing

- Double rig length & volume
- Congestion provided by regular array of vertical circular tubes:
  - 3.5-in (89 mm) tube dia.
  - 42 per 6-foot cube (+ corner supports)
  - "High" congestion level
- Ignition at 24 ft from end
  - 3x the run-up distance
  - 72 ft. vs. 24 ft.



Schematic of VCE Test Rig

Photograph of VCE Test Rig

12% Hydrogen (ER = 0.33)

14% Hydrogen (ER = 0.39)

Unconfined H_2 VCE Tests

- Hydrogen concentrations less than 10%H_2 will not contribute to a VCE
  - Conservative value as testing demonstrated 12%H_2 does not contribute
  - Makes a significant difference in VCE blast load prediction, as much of the flammable cloud is at concentrations below 10% [i.e., between LFL (4%) and 10%]
- Should consider potential for DDT at hydrogen concentrations above approximately 18%
  - Likelihood will depend on extent of congestion and confinement as well as size of flammable cloud interacting with congested/confined volume

- Jet Release H_2 VCE Tests

H_2 Jet Release Explosion Tests

- Jet release tests generally into open (unobstructed) environment
- Jet release tests with H_2 have shown the potential consequences of hydrogen jet release:
  - Can produce significant blast loads
    - Unlikely to be governing scenario for blast loading on buildings at an industrial site
    - May provide governing scenario in vicinity of release
- Large-scale test program carried out by Air Products illustrated on following slides (BakerRisk involved in evaluating test data)

H_2 Jet Release Air Products Test (1 of 2)

- Test conditions:
  - Horizontal release from ≈ 3 m elevation
  - 60 bar source pressure
  - ¾-inch and 2-inch release sizes
  - Initial release rates of ≈ 1 and 8 kg/s
  - Ignition ≈ 2 seconds after release initiated
- Load for 2-inch release (off centerline):
  - 10 meters: 0.43 barg (6.2 psig) 15 ms
  - 20 meters: 0.21 barg (3.0 psig) 13 ms

H_2 Jet Release Test Video (2" release)

- Vented H_2 Explosion Tests

Vented H_2 Explosion Tests

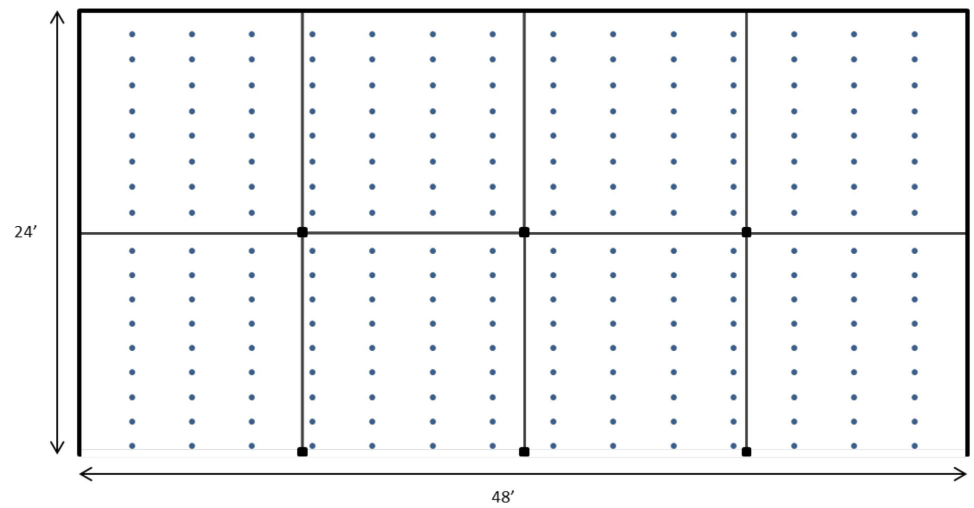
- Numerous vented H_2 explosion tests by multiple organizations have been performed
- Vented H_2 explosion shown the potential consequences of H_2 release into enclosure with delayed ignition:
  - Can produce significant blast loads from vented H_2 explosions,
  - Can achieve deflagration-to-detonation transition (DDT) at low congestion levels
- Single large-scale BakerRisk test program illustrated on following slides

Lean H_2 Vented Explosion Testing (1 of 2)

- Deflagration Load Generator (DLG)
  - 48 × 24 × 12 ft (14.6 × 7.3 × 3.7 m)
  - Enclosed volume of 13,800 ft^3 (392 m^3)
  - One open side sealed with plastic
- Test rig used by BakerRisk both to:
  - Produce blast loads to test structural response of full-scale structures
  - Investigate vented deflagration hazards

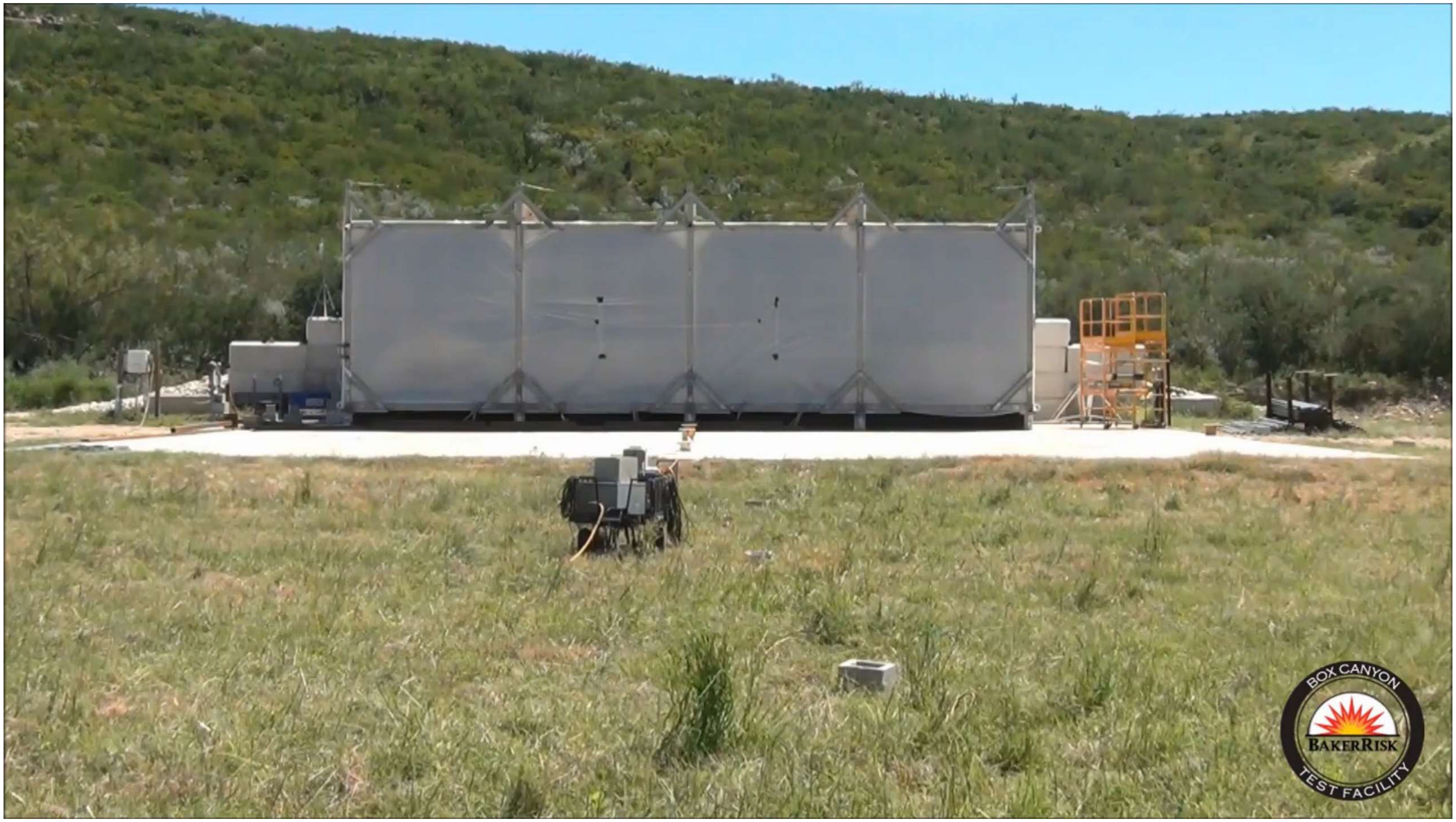
Lean H_2 Vented Explosion Testing (2 of 2)

- Very low congestion array of vertical circular tubes (next slide):
  - 2.0 and 2.375-in (60 mm) tube dia.
  - Pitch to diameter = 8.5
  - Area and vol. blockage ratios of 5% and 0.5%, respectively
  - Very low congestion level
- Center rear-wall ignition

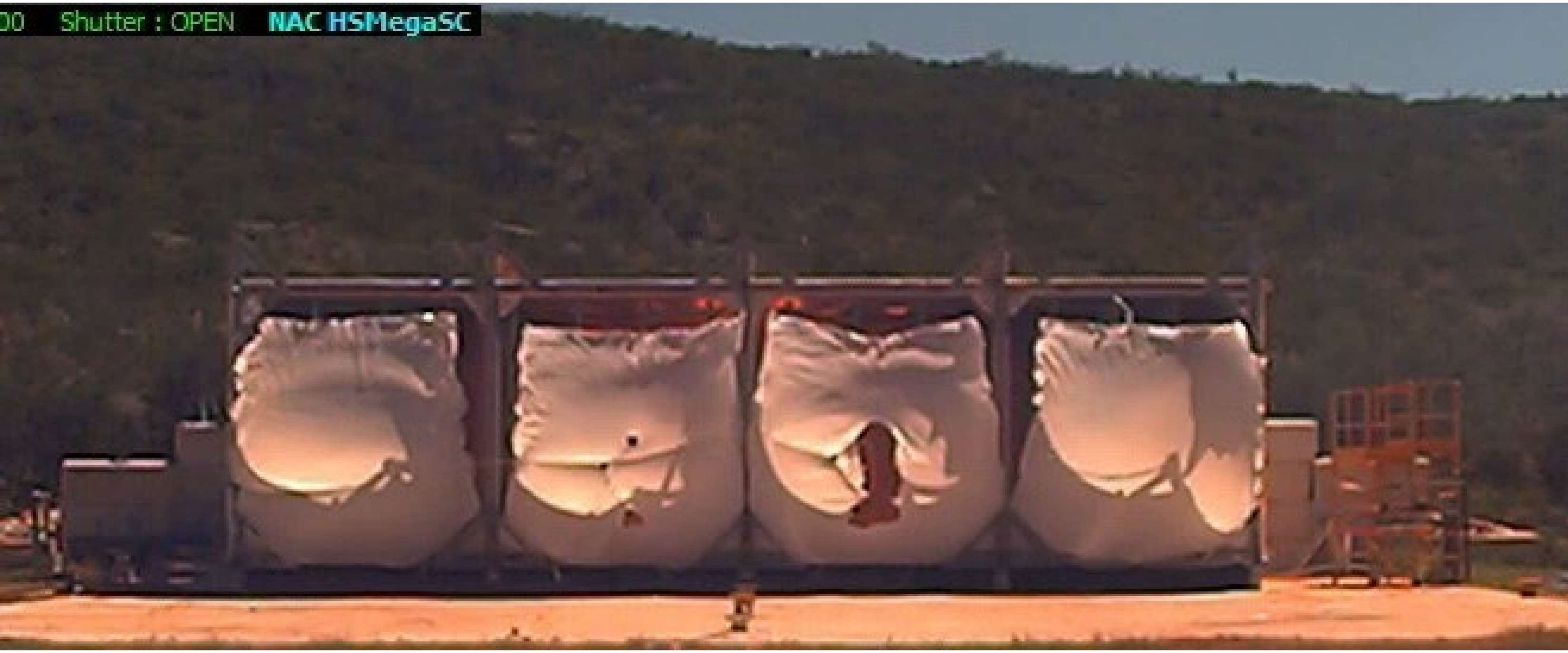


20% Hydrogen (ER = 0.60)

22.5% Hydrogen (ER = 0.69) – normal video



22.5% Hydrogen (ER = 0.69) – high-speed video



• H2 VCE Blast Load Prediction

VCE Blast Load Predictions (not H_2 specific)

- VCE blast load prediction methods:
  - TNT Equivalent (explicitly recommend not using)
  - Blast curve methods
    - Baker-Strehlow-Tang (BST)
    - TNO Multi-Energy Method (TNO MEM)
  - Computational fluid dynamic (CFD) methods
    - FLACS (GexCon)
    - Others are available
- VCE blast load function of:
  - Explosion energy (how much energy is released)
  - Flame speed (how fast this energy is released)
  - Standoff (how far away you are from the energy released)

Unconfined H_2 VCE Blast Loads

- Accident history has shown that:
  - Accidental H_2 releases at significant flow rates can generate large flammable clouds,
  - Delayed ignition can occur with such clouds, and
  - VCE if such clouds engulf an unconfined congested volume (+ delayed ignition), or if release forms strong turbulent jet
- Hydrogen flame speeds:
  - High vs. typical hydrocarbons at similar concentration (equivalence ratio)
  - Too low to produce blast load at $< 10\%$ H_2
  - DDT expected for concentrations approaching stoichiometric in moderate levels of congestion (even with no confinement)
    - Observed at 22% in BakerRisk's testing (vs. 30% stoichiometric)
    - Predicted at 18% for larger test rig configuration

• Conclusions

Closing Thoughts

1

H_2 poses unconfined VCE hazard

Can form a large flammable gas cloud near grade level and can have delayed ignition.

2

Accidental H2 VCEs are not rare

Incident history clearly illustrates this is a credible scenario

3

H_2 mixtures are subject to DDT

Observed in both unconfined and confined VCE testing.

4

Blast loads from H_2 VCEs can be large

Should account for potential loads in facility siting.

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